

Positive and negative sequence current injection to improve voltages under unbalanced faults

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Abstract—Grid faults constitute a series of unfortunate events that compromise power systems. With the increasing integration of renewables and their associated power electronics converters, the injected currents are controllable, but at the same time, they have to be limited so as not to damage the semiconductors. This poses the challenge to determine the combination of currents that improves the most the voltages at the point of common coupling. In this paper, such an issue is approached from an optimization perspective. Solving the optimization problem allows comparing its solutions with respect to the ones obtained by following the grid code control laws. Two fundamental scenarios are presented: one with a single converter, and another with two converters. Several parameters are varied for all kinds of faults to spot the changes on the currents, such as the severity of the fault, the distance of a hypothetical submarine cable, and the resistive/inductive ratio of the impedances. Overall the results indicate that injecting only reactive power is not always the preferable choice. While grid codes are not optimal, they can be regarded as near-optimal decision rules.

Index Terms—VSC, Grid-Support, Reference Optimization, Asymmetrical Fault, Current Saturation

I. INTRODUCTION

THE rise in renewable energies has carried along with it the inclusion of Voltage Source Converters (VSC) as a means of coupling energetic resources to the grid while providing controllability [1]–[3]. Adopting such power electronics equipment has induced a progressive shrinkage on synchronous generators’ influence in power systems. The high flexibility of VSC control enables advanced grid-support control, which could enhance the system performance during the fault and ensure a fast recovery after the fault clearance. However, compared to electrical machines, VSCs cannot withstand overloads [4]. Indeed, current (and also voltage) limitations cause VSC to behave differently. They reach what is called a saturated state. Many equilibrium points may arise as a result of that, especially in grids formed by multiple converters operating in critical conditions. The solution to such systems is also likely to become an arduous task to compute, as saturation states are defined by non-linear equations, or in more detail, by piecewise functions.

Not only do currents have to be constrained to not exceed the limitations, but they also have to collaborate on improving the voltages [5]. This becomes visible when looking at the requirements imposed by Transmission System Operators (TSO) in its grid codes [6], [7]. Although this was not the case years ago, when wind power represented a small percentage of the electricity mix, nowadays wind power plants have to control active and reactive power [8]. Besides, they have to

transiently support the faults. The latter aspect is often referred to as low voltage ride through (LVRT) [9], [10]. The traditional approach to raise the voltage at the point of common coupling is to inject reactive power proportionally to the severity of the fault [8], [11]. During the analysis of faults, it is often the case that voltages are decomposed into positive, negative, and zero sequence values. By doing so, the study of the fault is expected to be simplified, and in addition to that, some intuition can be built from inspecting the positive and negative sequence voltages. A concerning unbalanced fault is such that substantially decreases the positive sequence voltage with respect to the nominal voltage while the negative sequence voltage increases. Both sequences have to be thoroughly controlled, as discussed in [11], [12].

Nevertheless, for the most part, grid codes only specify reactive power injection during faults [13], [14]. This is because transmission networks are often considered to have an inductive characteristic. The influence of the grid impedance characteristics of the system optimized under an equilibrium state is covered in [12], where the authors express the currents to inject as a function of the voltage and the impedances. A recursive relation between the voltage and the current is found, which invalidates the possibility of working with a closed-form expression from where to compute the optimal currents solution. Expressions of the same nature are proposed in [15], where instead of attempting to solve the optimization problem, a control parameter is introduced. This takes various values, but no analysis is carried out to determine the optimal choice. The effect of varying this control parameter is studied in [16], although it is not computed with a systematic approach, but rather, manually. Reference [17] proposes a maximum allowed support (MAS) control scheme that is said to provide the maximum voltage support and simultaneously satisfying the current limitations. The study does not explicitly indicate how the current is distributed among the real and the imaginary positive and negative sequence components, and variations in input parameters are rather limited. Another voltage support scheme is presented in [18], where the injected currents depend neither on the active power nor the filter resistance. In addition, positive and negative sequence grid voltage values are imposed, which facilitates the obtention of the steady-state current values. A variation of the grid code requirements is depicted in [19]. The authors found it to provide better results than conventional grid codes. The majority of the grid support strategies described above are compared and summarized in [20]. It is worth mentioning that the systems under study considered in these references include a single VSC. Further conclusions are expected to be extracted from examining a two-converter case study.

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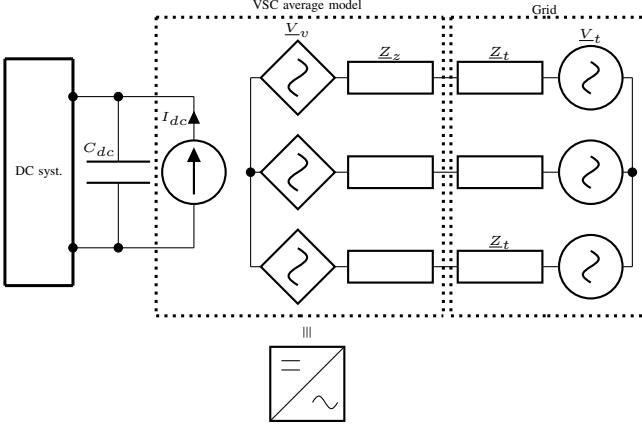


Fig. 1: Average model of a VSC connected to the grid

This paper proposes a methodology to identify the optimized system equilibrium point during the fault considering converters' current limitations. Two other control rules are implemented. One focuses on solving the optimization problem but in addition to the other constraints, it is restricted to only injecting reactive power. The third control rule follows the implementation of grid code specifications with its characteristic droop profile. These three options are tested for both balanced and unbalanced faults, where this last category includes the line to ground, the line to line, and the double line to ground faults. First, a basic system with a single converter is studied. Then, the analysis is repeated for a system with two converters in order to identify their interaction in saturated states.

Two main contributions come from this paper. On the one hand, it indicates the preferable injected currents under diverse conditions. A deeper understanding of the optimality of the solutions is expected to be gained from it. On the other hand, comparisons between the optimal solution and the one obtained by following the grid code are presented. An assessment about the convenience of grid codes to support faults can be derived, which should be useful when proposing future modifications in order to evolve towards more resilient grids.

II. FORMULATION

A. System modeling

VSCs are elements that interconnect DC systems with AC systems. As shown in Fig. 1, they can be modeled following the so-called average model, where the switchings of the semiconductors are excluded. The VSC has been assumed to be connected to the AC grid with a filter in between denoted by Z_z . The control strategy of the VSC consists of adjusting the voltages appropriately so that currents can indirectly meet the references [21].

Power systems are likely to involve more than a single converter. Therefore, the modeling is approached from a generalized perspective. Fig. 2 presents the modeling for a system with n converters. They are connected to a grid which has been split into a passive part, only formed by impedances and denoted by its admittance matrix \underline{Y}_g , and an active part,

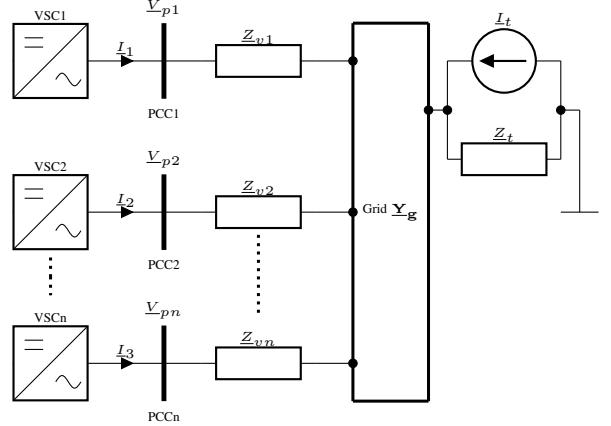


Fig. 2: Single-phase representation of a complete system

modeled with a Norton equivalent. Compared to dealing with a Thevenin equivalent, the Norton equivalent simplifies the formulation since it does not create an additional bus. The VSCs are treated as current sources that inject currents of the form of $I_k \forall k \in [1, \dots, n]$. Additional impedances denoted by Z_{vk} connect the point of common coupling to the grid. Such point of common coupling is precisely where the voltages ought to be improved.

The relationship between currents and voltages can be established with an analysis in the natural reference frame or by employing symmetrical components as in [22]. Although both approaches are equally valid, working in the natural reference frame allows studying the system with greater flexibility, as only the particular elements of the admittance matrices that depend on the fault admittance experience changes. No other modifications in the topology have to be considered. Consequently, voltages and currents are related by

$$\begin{pmatrix} \underline{I}_1 \\ \underline{I}_2 \\ \vdots \\ \underline{I}_n \\ \underline{I}_t \end{pmatrix} = \begin{pmatrix} \underline{Y}_{v1} & 0 & \dots & 0 & -\underline{Y}'_{v1} \\ 0 & \underline{Y}_{v2} & \dots & 0 & -\underline{Y}'_{v2} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \dots & \underline{Y}_{vn} & -\underline{Y}'_{vn} \\ -\underline{Y}'^T_{v1} & -\underline{Y}'^T_{v2} & \dots & -\underline{Y}'^T_{vn} & \underline{Y}_g \end{pmatrix} \begin{pmatrix} \underline{V}_{p1} \\ \underline{V}_{p2} \\ \vdots \\ \underline{V}_{pn} \\ \underline{V}_g \end{pmatrix}. \quad (1)$$

For a given converter k , its injected currents and its associated voltages at the point of common coupling are further developed as

$$\begin{aligned} \underline{I}_k &= [I_k^{(a)}, I_k^{(b)}, I_k^{(c)}]^T \\ \underline{V}_{pk} &= [V_{pk}^{(a)}, V_{pk}^{(b)}, V_{pk}^{(c)}]^T \end{aligned} \quad (2)$$

i.e., they contain the a , b and c phase values. Since VSCs cannot inject zero sequence currents, the formulation of the problem also imposes

$$I_k^a + I_k^b + I_k^c = 0 \quad \forall k \in [1, \dots, n]. \quad (3)$$

Voltages and currents are related via admittance matrices of the form \underline{Y}_{vk} , which in normal operating conditions follow

$$\underline{Y}_{vk} = \begin{pmatrix} \frac{1}{Z_{vk}} & 0 & 0 \\ 0 & \frac{1}{Z_{vk}} & 0 \\ 0 & 0 & \frac{1}{Z_{vk}} \end{pmatrix}. \quad (4)$$

In case a fault occurs at the buses interconnected by \underline{Z}_{vk} , elements $1/\underline{Z}_f$ are added by observation, where \underline{Z}_f denotes the fault impedance.

On the contrary, the admittance matrix \underline{Y}_g is a $3n_g \times 3n_g$ matrix also built by observation. The object \underline{I}_t is a vector of dimensions $3 \times n_g$ which accounts for the injected currents into the grid denoted by \underline{Y}_g . All its elements are null except for three entries that consider the injected currents from the Norton equivalent of the grid. Matrices of the form \underline{Y}'_{vk} are $3 \times 3n_g$ objects constituted by elements $1/\underline{Z}_{vk}$. In a realistic scenario, the grid \underline{Y}_g may be partially constituted by active and reactive power loads, i.e., PQ buses. They can be either ignored if the current they consume is assessed to be comparatively smaller than the fault current, or they can be modeled as constant admittances. No PQ loads have been considered in the case studies shown in this paper.

The final goal of the modeling is the obtention of voltages. They are computed from (1) by operating the product between the inverse of the full admittance matrix and the currents' vector. In order to have a clearer comprehension of the voltages, they are eventually converted into symmetrical components by means of Fortescue's transformation [23]:

$$\begin{pmatrix} \underline{V}_{pk}^0 \\ \underline{V}_{pk}^+ \\ \underline{V}_{pk}^- \end{pmatrix} = \frac{1}{3} \begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix} \begin{pmatrix} \underline{V}_{pk}^a \\ \underline{V}_{pk}^b \\ \underline{V}_{pk}^c \end{pmatrix}, \quad (5)$$

where $a = e^{j\frac{2\pi}{3}}$.

B. Optimization problem

Positive sequence voltages have to be maximized while negative sequence voltages have to be minimized. The zero sequence component of the voltages is a magnitude likely to become non-null under asymmetrical faults. Nevertheless, as VSC are unable to inject zero sequence currents, it will remain an uncontrolled variable in the sense that no efforts will be made towards reducing it. Current saturation restrictions imposed by the VSC characteristics have to be respected. This applies to each phase of each converter. Therefore, the generic optimization problem is

$$\begin{aligned} \min_{\underline{I}} \quad & \sum_{k=1}^n \left[\lambda_k^+ |(1 - |\underline{V}_{pk}^+(\underline{I})|)| + \lambda_k^- |(0 - |\underline{V}_{pk}^-(\underline{I})|)| \right], \\ \text{s.t.} \quad & \max(\underline{I}_k^a, \underline{I}_k^b, \underline{I}_k^c) \leq I_{\max,k} \quad \forall k \in [1, \dots, n], \end{aligned} \quad (6)$$

where the positive and negative sequence components of voltages \underline{V}_{pk} are symbolically expressed as functions of the currents, and $I_{\max,k}$ is the maximum allowed current by the k converter. It has been assumed that voltages at each phase of the converter do not surpass the limitations, which seems a fair assumption considering that voltages decreases substantially during faults. Ignoring voltage limitations tends to be a commonality in the literature as well.

The results gathered in this paper are computed with Python 3.9.1 and the aid of the Mystic package, a highly-constrained non-convex optimization framework [24], [25]. A differential global optimization solver has been employed with a relative precision up to $1e - 6$.

C. Grid code rules

In order to improve voltages during faults, grid code control rules typically impose injections of currents proportional to the voltage drop [8], [26]. When defined as generic piecewise functions, for the positive sequence

$$\begin{cases} |\underline{I}_k^+| = 0 & |\underline{V}_{pk}^+| \geq V_{\text{high}}^+ \\ |\underline{I}_k^+| = k_p(V_{\text{high}}^+ - |\underline{V}_{pk}^+|) & V_{\text{low}}^+ \leq |\underline{V}_{pk}^+| < V_{\text{high}}^+ \\ |\underline{I}_k^+| = I_{\max,k} & |\underline{V}_{pk}^+| < V_{\text{low}}^+ \end{cases} \quad (7)$$

whereas for the negative sequence

$$\begin{cases} |\underline{I}_k^-| = 0 & |\underline{V}_{pk}^-| \leq V_{\text{low}}^- \\ |\underline{I}_k^-| = k_n(|\underline{V}_{pk}^-| - V_{\text{low}}^-) & V_{\text{low}}^- \leq |\underline{V}_{pk}^-| < V_{\text{high}}^- \\ |\underline{I}_k^-| = I_{\max,k} & |\underline{V}_{pk}^-| > V_{\text{high}}^- \end{cases} \quad (8)$$

where the values of the constants are gathered in Table IV. Constants k_p and k_n , which represent the slope of the droop, are set as fixed quantities. The converter would therefore operate at saturated conditions during extreme faults because either the positive sequence voltage would reach the lower threshold V_{low}^+ or the negative sequence voltage would surpass the upper threshold V_{high}^- . However, in severe faults it is still possible that both limits are surpassed, or at least, approached. In case (7) and (8) where applied simultaneously, the required current to be injected by the VSC could potentially exceed the $I_{\max,k}$ limitation. Thus, it makes sense to establish a prioritization.

This paper considers the two straightforward prioritizations. One strategy is to have the positive sequence current following (7) and injecting the maximum allowed negative sequence current so as not to exceed the current limitations in any phase. This methodology will be commonly referred to as GCP. The other option, abbreviated as GCN, is concerned with obeying (8) and analogously injecting the maximum positive sequence current that respects the limits. During all situations, the converters work under saturated conditions (current limits reached) as the non-prioritized current is set to the allowed maximum. Also, only reactive power is injected. The procedure to determine the non-prioritized current is depicted below.

Consider a generic distribution of positive and negative sequence voltages in the complex plane, as in Fig. 3. Phase currents are related to zero, positive and negative sequence components by

$$\begin{pmatrix} \underline{I}_a \\ \underline{I}_b \\ \underline{I}_c \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix} \begin{pmatrix} \underline{I}^0 \\ \underline{I}^+ \\ \underline{I}^- \end{pmatrix} \quad (9)$$

where \underline{I}^0 is null as the VSC is incapable of injecting it. The k index related to identifying a given VSC has been omitted to alleviate the notation. Explicitly, (9) becomes

$$\begin{cases} \underline{I}_a = \underline{I}^+ + \underline{I}^- \\ \underline{I}_b = a^2 \underline{I}^+ + a \underline{I}^- \\ \underline{I}_c = a \underline{I}^+ + a^2 \underline{I}^- \end{cases} \quad (10)$$

Then, the absolute value of the three phase currents is set to the limit I_{\max} . The goal of doing so is to determine the maximum current that causes one phase to reach saturation while the

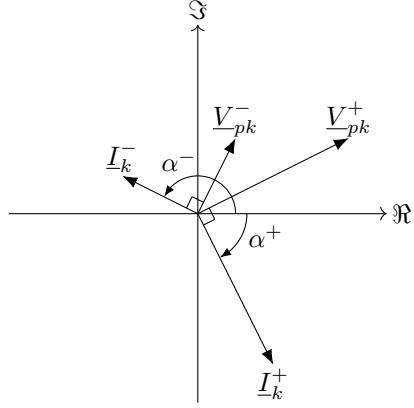


Fig. 3: Overview of positive and negative sequence voltages and currents following grid code rules

two others operate under the limits. This will act as the most restrictive option. Consequently, squaring the currents yields

$$\left\{ \begin{array}{l} I_{\max}^2 = (I_{re}^+ + I_{re}^-)^2 + (I_{im}^+ + I_{im}^-)^2 \\ I_{\max}^2 = (-\frac{1}{2}I_{re}^+ + \frac{\sqrt{3}}{2}I_{im}^+ - \frac{1}{2}I_{re}^- - \frac{\sqrt{3}}{2}I_{im}^-)^2 \\ \quad + (-\frac{1}{2}I_{im}^+ - \frac{\sqrt{3}}{2}I_{re}^+ - \frac{1}{2}I_{im}^- + \frac{\sqrt{3}}{2}I_{re}^-)^2 \\ I_{\max}^2 = (-\frac{1}{2}I_{re}^+ - \frac{\sqrt{3}}{2}I_{im}^+ - \frac{1}{2}I_{re}^- + \frac{\sqrt{3}}{2}I_{im}^-)^2 \\ \quad + (\frac{\sqrt{3}}{2}I_{re}^+ - \frac{1}{2}I_{im}^+ - \frac{\sqrt{3}}{2}I_{re}^- - \frac{1}{2}I_{im}^-)^2 \end{array} \right. \quad (11)$$

It can be seen that each phase current, set at the allowed maximum, depends on four components, that is, I_{re}^+ , I_{im}^+ , I_{re}^- and I_{im}^- . When the positive sequence is prioritized (GCP), the grid code rules in (7) determine the absolute value of the positive sequence current while its direction in the complex plane is extracted by shifting it $-\frac{\pi}{2}$ with respect to \underline{V}^+ , as seen in Fig. 3. Thus, I_{re}^+ and I_{im}^+ would be known beforehand, and only the two remaining components I_{re}^- and I_{im}^- have to be computed from (11) for each phase. To do so, one component has to be expressed as a function of the other. This carries no extra complexity considering that phasor \underline{V}^- is fully known, and so the direction of \underline{I}^- has to be shifted $\frac{\pi}{2}$ from it. Making use of the relation

$$\tan(\alpha^-) = \frac{I_{im}^-}{I_{re}^-}, \quad (12)$$

current I_{im}^- can be expressed as a function of I_{re}^- , for instance, and therefore there is only one unknown in each expression of (11). Then, the resulting quadratic equations are solved for I_{re}^- and the associated I_{im}^- is found with (12).

Note that six $[I_{re}^-, I_{im}^-]$ pairs of solutions would be obtained in total. Three of them have to be discarded because they do not follow the pre-established direction of \underline{I}^- (due to the quadratic characteristic of (11)). Out of the remaining three, the one with the smallest absolute value is picked. This way it is ensured that current saturation is only reached in one phase, while the other two operate below their limits.

An analogous procedure as the one described above applies to computing the positive sequence current in case the negative sequence component is prioritized (GCN).

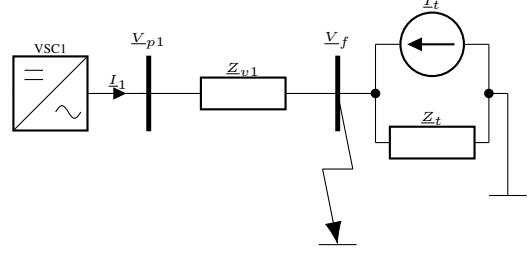


Fig. 4: Single-phase representation of the single converter system under study

D. Summary of support techniques

The paper evaluates and compares three support strategies, which are:

- OPT: corresponds to the solution of the optimization problem in (6), particularized for each system. It provides, by definition, the best solution. Both active and reactive powers can be injected.
- GCP: is the application of the grid code rule shown in (7). It prioritizes positive sequence current injection.
- GCN: follows the grid code negative sequence current injection shown in (8). Just like GCP, the current limitation is reached in one phase, and only reactive power can be injected.

III. SINGLE CONVERTER CASE STUDY

The analysis is first performed considering a one-converter case study as the one depicted in Fig. 4. A fault is caused at the point of connection of the grid. The impedances that model the fault are set accordingly to the type of fault, i.e., balanced or unbalanced (line to ground, line to line or double line to ground). The goal is to improve the voltage V_{p1} by injecting the optimal \underline{I}_1^a , \underline{I}_1^b and \underline{I}_1^c currents.

Three parametric studies are performed. One considers variations in the fault impedance. This case is explicitly described in order to exemplify the formulation. Another study analyzes a varying R_1/X_1 ratio, which stands for the proportion between the resistive and the inductive parts that compose the impedance Z_{v1} . This ratio is modified while the absolute value of the impedance is kept constant. The third case presents the effect of increasing the distance of a hypothetical submarine cable.

A. Fault impedance variation analysis

For a single converter system as the one depicted in Fig. 4, the fault impedance connected to the bus at voltage \underline{V}_f is responsible for identifying the fault. Explicitly, voltages and currents are related by

$$\begin{pmatrix} \underline{I}_1^a \\ \underline{I}_1^b \\ \underline{I}_1^c \\ \underline{I}_t^a \\ \underline{I}_t^b \\ \underline{I}_t^c \end{pmatrix} = (\underline{\mathbf{Y}}_v + \underline{\mathbf{Y}}_f) \begin{pmatrix} \underline{V}_{p1}^a \\ \underline{V}_{p1}^b \\ \underline{V}_{p1}^c \\ \underline{V}_f^a \\ \underline{V}_f^b \\ \underline{V}_f^c \end{pmatrix}, \quad (13)$$

TABLE I: System parameters for the one-converter case

Parameter	Value
V_t	1.00
I_{\max}	1.00
Z_{v1}	$0.01 + j0.05$
Z_t	$0.01 + j0.1$
$[\lambda_1^+, \lambda_1^-]$	[1, 1]

where the admittance matrix has been split into two parts: $\underline{\mathbf{Y}}_v$ represents the non-faulted admittance matrix of the system, whereas $\underline{\mathbf{Y}}_f$ is constituted by the admittances that intervene in the fault. This way, the admittance matrices are defined as

$$\underline{\mathbf{Y}}_v = \begin{pmatrix} Y_{v1} & 0 & 0 & -Y_{v1} & 0 & 0 \\ 0 & Y_{v1} & 0 & 0 & -Y_{v1} & 0 \\ 0 & 0 & Y_{v1} & 0 & 0 & -Y_{v1} \\ -Y_{v1} & 0 & 0 & Y_{v1} + Y_t & 0 & 0 \\ 0 & -Y_{v1} & 0 & 0 & Y_{v1} + Y_t & 0 \\ 0 & 0 & -Y_{v1} & 0 & 0 & Y_{v1} + Y_t \end{pmatrix} \quad (14)$$

where $Y_{v1} = 1/Z_{v1}$ and $Y_t = 1/Z_t$.

On the other hand, the fault admittance $\underline{\mathbf{Y}}_f$ is fully dependent on the fault, and therefore, it is built by observation. The optimization problem for the one case converter reads

$$\begin{aligned} \min_{I_1^a, I_1^b, I_1^c} \quad & \lambda_1^+ |(1 - |V_{p1}^+(I_1^a, I_1^b, I_1^c)|)| \\ & + \lambda_1^- |(0 - |V_{p1}^-(I_1^a, I_1^b, I_1^c)|)|, \\ \text{s.t.} \quad & \max(I_1^a, I_1^b, I_1^c) \leq I_{\max}, \end{aligned} \quad (15)$$

Because of the nature of the converter, it is also imposed that the sum of the three phase currents becomes null. The procedure to solve the optimization problem is first responsible for initializing the admittances matrices $\underline{\mathbf{Y}}_v$ as in (14), and then, constructing $\underline{\mathbf{Y}}_f$. Next, currents are initialized to a random array of values, for instance. The Mystic package is subsequently called to solve the optimization problem stated in (15) up to a given relative precision δ , being $\delta = 1e-6$ for example. Positive and negative sequence voltages are evaluated to determine the optimality of the solution by means of (5). In the case of sweeping a range of n scenarios, this process is repeated n times. Currents are eventually also transformed to positive and negative sequence values since the final goal is to evaluate their values in this frame of reference. Unless noted otherwise, the corresponding baseline parameters of the system in Fig. 4 are indicated in Table I.

Solving the problem with the aforementioned steps for a balanced fault yields the results shown in Fig. 5, where impedance Z_x denotes the fault impedance connected to each phase. The results suggest that the OPT case is the preferred one, as its associated objective function is always the smallest, as expected. This optimal solution is achieved by distributing the currents between the real and imaginary parts. The imaginary current remains slightly larger than the real current (in absolute value). This is the main difference between OPT and the grid code implementation found in GCP and GCN. These two strategies always specify a null real current in both sequences, and in this case, they employ their full capability for the imaginary positive sequence current. Therefore, their objective functions and voltage profiles become identical, simply put, because this is a balanced fault.

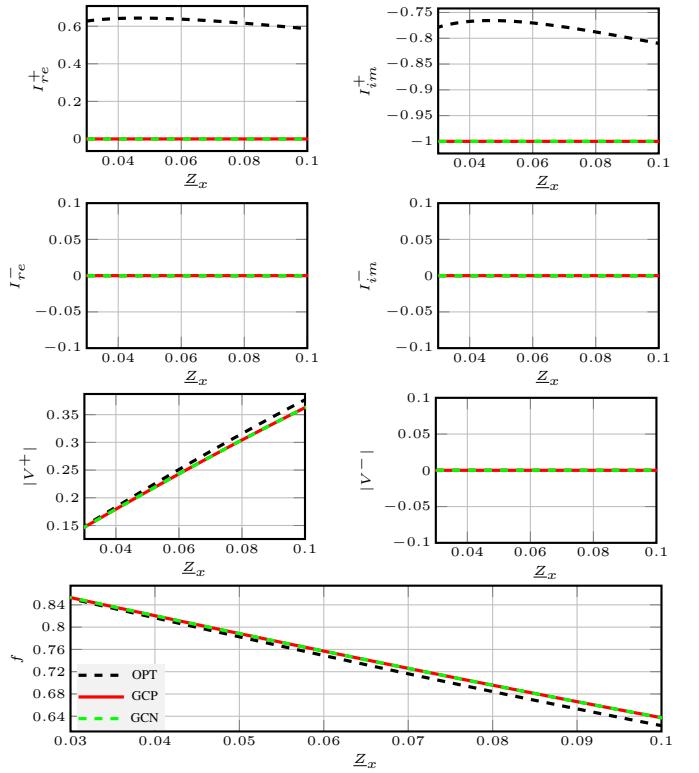


Fig. 5: Influence of the currents on the objective function for the balanced fault with a varying fault admittance, one converter case

Significantly different results are obtained in the case of a line to line fault, as shown in Fig. 6. This unbalanced fault causes the optimal currents to be null in the positive sequence, so all current capability is employed for the negative sequence. Severe faults require a large real current (in absolute value), whereas in the case of less extreme faults, the imaginary current tends to the maximum, i.e. 1. OPT yields the smallest $|V^-|$ and also the smallest $|V^+|$. Even though the real current is kept at zero for GCP and GCN, their imaginary currents vary significantly across the range of Z_x values. GCP tends to approach the results provided by OPT for large Z_x , whereas GCN evolves in the contrary direction. That is, for low fault impedances, GCP prioritizes injecting current in the positive sequence whereas GCN does the same for the negative sequence, as expected. As a consequence, positive sequence voltages in the case of GCP are initially superior to the ones obtained with GCN, and the contrary applies to the negative sequence voltages. The situation is reversed around $Z_x \approx 0.1$. Since the fault is not that severe, much of the current capability is employed in the non-prioritized sequence in order to reach saturation. In the end, there is an almost constant minimal difference between OPT and both GCP and GCN. All three objective functions are nearly the same. One relevant partial conclusion is the fact that for this line to line fault, the optimal approach is to inject null positive sequence currents.

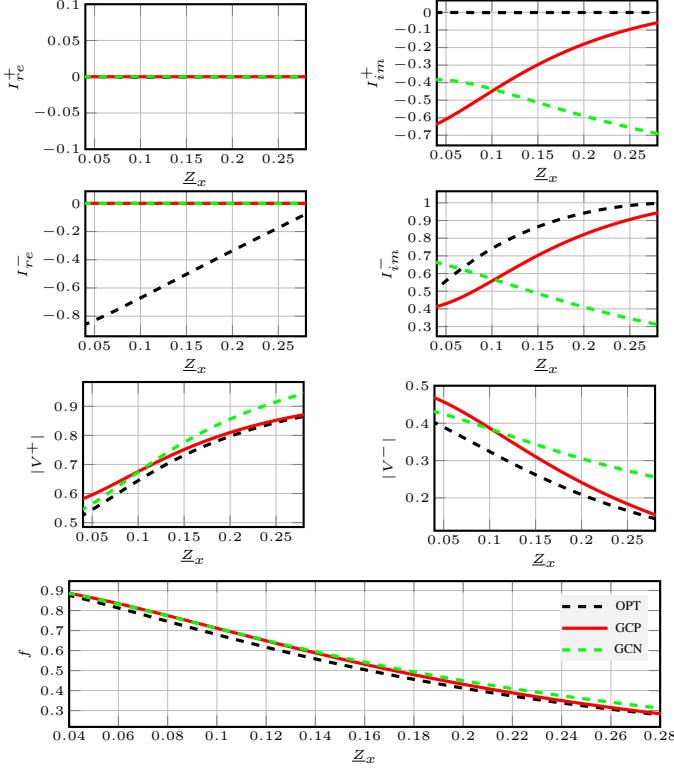


Fig. 6: Influence of the currents on the objective function for the line to line with a varying fault admittance, one converter case

B. R_1/X_1 variation analysis

The R_1/X_1 variation analysis performs a swept for a range of a varying angle of the Z_{v1} impedance, while the absolute value is preserved. The goal of this study is to determine how this affects the distribution of currents between the real and the imaginary part. The results in Fig. 7 for the OPT case show that despite an increase in the resistive part of the impedance, the currents remain nearly constant for all the range of values. Most of the current capability is dedicated to I_{im}^+ and I_{re}^- . The converter injects a non-negligible active power, as the injected complex power remains around $0.30 + j0.45$.

For large R_1/X_1 differences between the objective functions of OPT and GCP and GCN are acute due to the incapability of injecting real current. The OPT option achieves a larger positive sequence voltage than both GCP and GCN for all ranges of values. Although the negative sequence voltage obtained with OPT is initially larger, it is further reduced with increases in R_1/X_1 , whereas this same voltage tends to grow for GCP and GCN. Despite the fact that GCP prioritizes active current, as the fault is not extreme and it has been imposed that the converter has to operate under saturated conditions, the GCP strategy injects more current in the negative sequence than in the positive sequence. The contrary applies to the GCN option. Therefore, GCN yields larger $|V^+|$ and $|V^-|$ voltages compared to GCP. In the end, the objective function is practically the same for both choices.

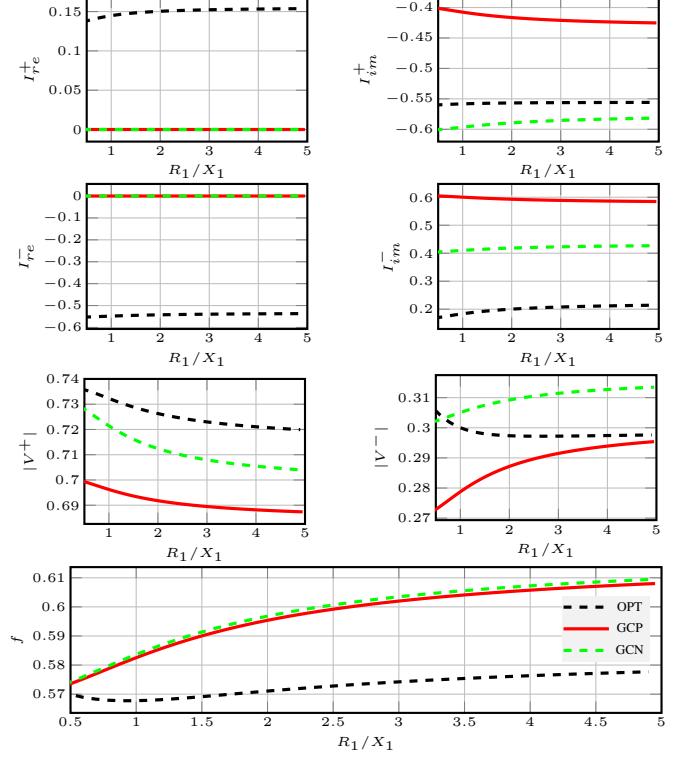


Fig. 7: Influence of the currents on the objective function for the line to ground fault with a varying R_1/X_1 ratio and a fault impedance $Z_{ag} = 0.01$

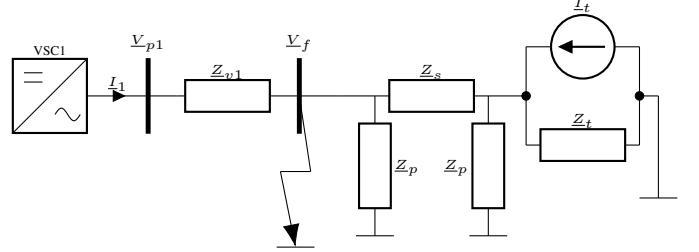


Fig. 8: Single-phase representation of the single converter connected to a system with a cable

C. Cable length variation analysis

Fig. 8 represents the third parametric study regarding single converter systems, which deals with a hypothetical submarine cable modeled with its π equivalent. The data selected to model the cable are extracted from [27] and adapted to per unit values. Table II presents them. The followed approach to analyze the system is identical to the previous ones, except for the reduction of the set of elements including the cable and the grid. The corresponding Thevenin equivalent is defined by

TABLE II: System parameters for the one-converter case

Parameter	Value	Units
Z_s	$6.674 \cdot 10^{-5} + j2.597 \cdot 10^{-4}$	pu/km
Z_p	$-j77.372$	pu-km

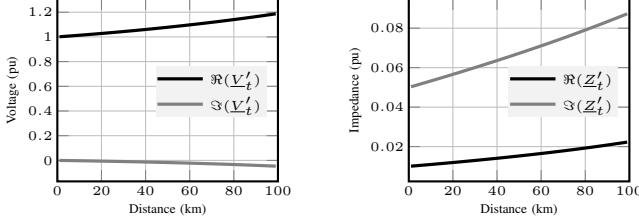


Fig. 9: Influence of the cable distance on the Thevenin voltage and impedance

$$\begin{cases} \underline{V}'_t = \frac{\underline{Z}_p \underline{Z}_p}{2\underline{Z}_t \underline{Z}_p + \underline{Z}_p \underline{Z}_s + \underline{Z}_p \underline{Z}_p + \underline{Z}_t \underline{Z}_s} \\ \underline{Z}'_t = \frac{\underline{Z}_p \underline{Z}_p \underline{Z}_t + \underline{Z}_p \underline{Z}_p \underline{Z}_s + \underline{Z}_p \underline{Z}_s \underline{Z}_t}{2\underline{Z}_p \underline{Z}_t + \underline{Z}_s \underline{Z}_p + \underline{Z}_s \underline{Z}_t + \underline{Z}_p \underline{Z}_p} \end{cases} \quad (16)$$

Similarly as before, a Norton equivalent is preferred. The current \underline{I}'_t is simply equal to $\underline{V}'_t/\underline{Z}'_t$, which yields a basic system as the one in Fig. 4.

The analysis performed considers a cable with a varying length, up to 100 km. Its impact on the Thevenin equivalent parameters are shown in Fig. 9. The voltage experiences a subtle increase, while the imaginary part of the equivalent impedance grows considerably with distance, yet the $\Re(\underline{Z}'_t)/\Im(\underline{Z}'_t)$ ratio tends to rise.

The options OPT, GCP and GCN are again evaluated, as depicted in Fig. 10. Increasing the cable distance causes the negative sequence voltage to grow, while the positive sequence voltage also tends to grow. This phenomenon differs from the profiles obtained in Fig. 6 and 7, where both voltages either simultaneously approached the objective value (1 and 0 respectively), or distanced from it. Thus, it makes sense that larger distances imply a lower I_{im}^+ current in the case of the grid code implementation, while the less convenient growing negative sequence voltages force an increment in I_{im}^- . Most of the current capability is precisely devoted to this negative sequence imaginary current. The OPT option achieves a more favorable objective function value than GCP and GCN by keeping the positive sequence currents practically constant, increasing I_{re}^- (in absolute value), and decreasing I_{im}^- , which is the inverse trend followed by GCP and GCN. Surprisingly, in the OPT case, the VSC would have to inject a tiny negative active power, that is, this active power should flow from the grid to the converter.

IV. TWO-CONVERTER CASE STUDY

A two-converter case is proposed in order to spot the interaction between both converters and compare the performance of the optimization with the grid code rules. Fig. 11 shows a single-phase representation of the system under study. The converters are coupled to the grid by means of slightly different impedances \underline{Z}_{v1} and \underline{Z}_{v2} . Table III shows their values together with other input data.

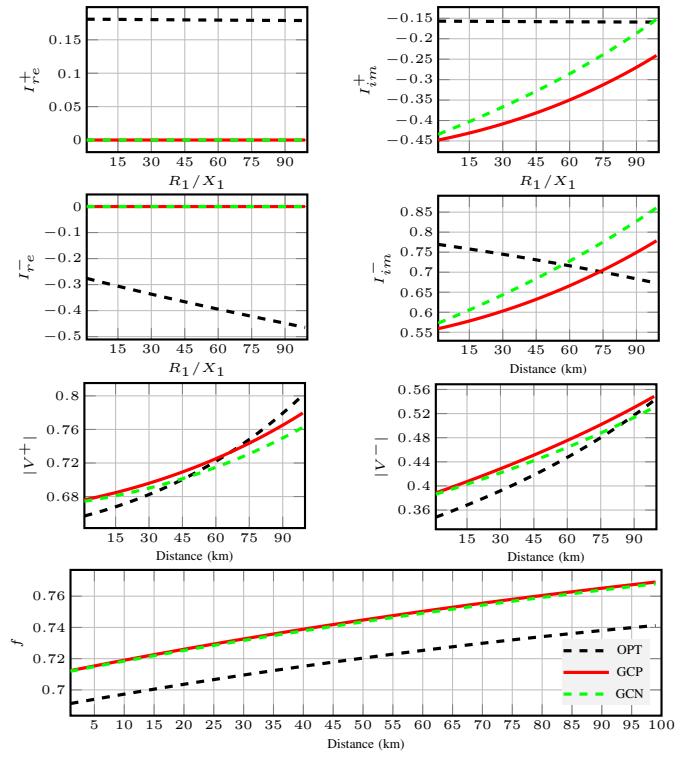


Fig. 10: Influence of the currents on the objective function for a line to line fault with $Z_{ab} = 0.1$ and a varying cable distance

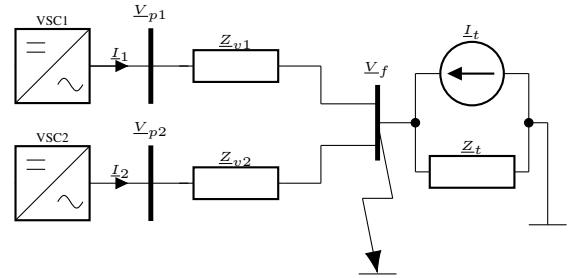


Fig. 11: Single-phase representation of the two-converter system under study

TABLE III: System parameters for the two converter case

Parameter	Value
V_t	1.00
I_{max}	1.00
\underline{Z}_{v1}	$0.01 + j0.05$
\underline{Z}_{v2}	$0.01 + j0.06$
\underline{Z}_t	$0.01 + j0.1$
$[\lambda_1^+, \lambda_1^-, \lambda_2^+, \lambda_2^-]$	[1, 1, 1, 1]

Analogous to the one-converter situation, the optimization problem becomes

$$\begin{aligned} \min_{\underline{I}_1^a, \underline{I}_1^b, \underline{I}_1^c, \underline{I}_2^a, \underline{I}_2^b, \underline{I}_2^c} & \lambda_1^+ |(1 - |\underline{V}_{p1}^+|)| + \lambda_1^- |(0 - |\underline{V}_{p1}^-|)| \\ & + \lambda_2^+ |(1 - |\underline{V}_{p2}^+|)| + \lambda_2^- |(0 - |\underline{V}_{p2}^-|)|, \\ \text{s.t. } & \max(\underline{I}_1^a, \underline{I}_1^b, \underline{I}_1^c) \leq I_{\max,1}, \\ & \max(\underline{I}_2^a, \underline{I}_2^b, \underline{I}_2^c) \leq I_{\max,2} \end{aligned} \quad (17)$$

where the dependence of the currents on the voltages has been omitted. The application of the grid code is the same as before, in the sense that the injection of current \underline{I}_1 only depends on \underline{V}_{p1} , and \underline{I}_2 is only a function of \underline{V}_{p2} .

A. Fault impedance variation analysis

The results associated to a line to ground fault with a varying fault impedance are shown in Fig. 12. Differences in the objective function are negligible for small values of \underline{Z}_x , that is, for strong faults. Nevertheless, the converter operates in saturated conditions in all cases. Due to the fact that $\underline{Z}_{v1} \neq \underline{Z}_{v2}$, the distribution of the current capability varies. For instance, in the positive sequence, VSC2 injects more imaginary current (in absolute value), which makes sense considering that $\Im(\underline{Z}_{v2}) > \Im(\underline{Z}_{v1})$. However, the absolute value of I_{im}^+ becomes larger for VSC1, which seems counterintuitive. Since the fault is for the most part not extreme ($|V^+| \approx 0.75$ and $|V^-| \approx 0.25$), GCP ends up injecting more negative sequence current whereas GCN injects more positive sequence current. This is translated into having larger positive sequence voltages for GCN and smaller negative sequence voltages for GCP. The same pattern was observed in Fig. 7. OPT remains as the choice that balances both sequences and manages to minimize the objective function.

B. R/X variation analysis

The angle variation of the impedance of connection is applied to only \underline{Z}_{v1} in order to spot more clearly the differences in the distribution of currents between the sequences. For a line to line fault with $\underline{Z}_x = 10$, Fig. 13 indicates that since R_2/X_2 is constant, the currents injected by VSC2 experience tiny changes. On the contrary, the currents injected by VSC1 change more significantly. The optimal strategy is to inject null currents in the positive sequence so that all current capability is employed to reduce the negative sequence voltage. This same approach was found to be optimal in the one-converter case, as shown in Fig. 6. As a consequence, the positive sequence voltage in the OPT case becomes smaller than the one obtained for GCP and GCN, yet the reduction on the negative sequence voltage is more substantial, which causes the objective function to be reduced by more than 10%. Out of the multiple faults analyzed in this paper, this is the one where differences in the objective function are larger.

V. CONCLUSION

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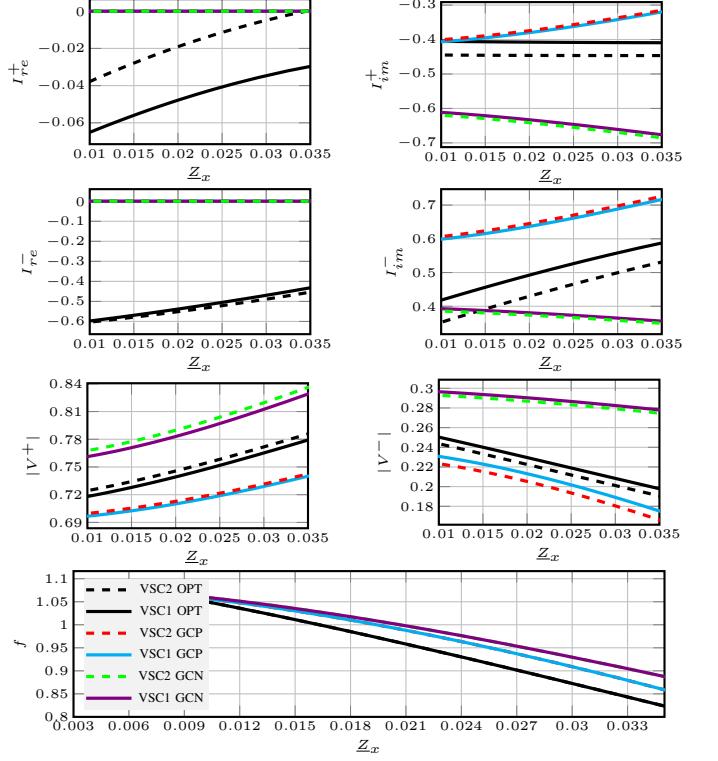


Fig. 12: Influence of the currents on the objective function for the line to ground fault with a varying fault impedance

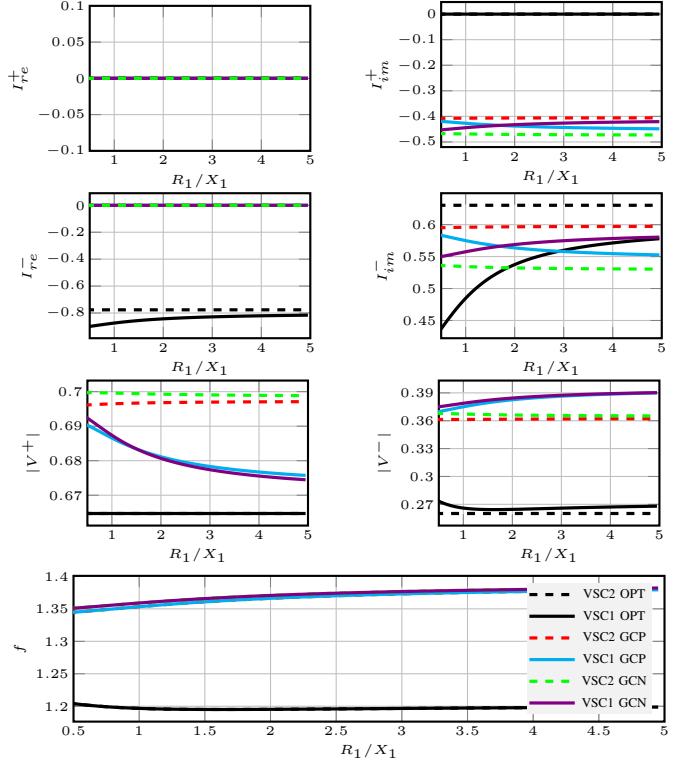


Fig. 13: Influence of the currents on the objective function for the line to ground fault with a varying R_1/X_1 ratio and $Z_x = 10$

ACKNOWLEDGMENT

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APPENDIX

TABLE IV: Grid code constants

Parameter	Value
V_{high}^+	0.9
V_{low}^+	0.4
V_{high}^-	0.6
V_{low}^-	0.1
k_p	2.0
k_n	2.0

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